THE EFFECT OF BACKGROUND LUMINANCE AND AMBIENT ILLUMINATION ON COLOR DISCRIMINATION IN A CRT DISPLAY.

by

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SUMMARY PAGE

PROBLEM

To determine the best raster luminance to use for color discriminability with CRT displays under various ambient illuminations and with various target sizes.

FINDINGS

Under dark ambient illumination, performance was significantly better with an intermediate raster luminance than with a low raster. The opposite was found under bright ambient illumination. A target with a small visual angle (7 min of arc) yielded significantly poorer performance on a discrimination task than a target with a larger visual angle (1.4 deg).

APPLICATION

The best color discrimination for CRT generated colors occurs when the background luminance is set to an intermediate level. This means that under dark ambient conditions, the raster luminance should be set to an intermediate level but reduced as the ambient illumination increases.

ADMINISTRATIVE INFORMATION

This research was conducted as part of the Naval Medical Research and Development Command Work Unit M0100.001-1022--"Enhanced performance with visual sonar displays." It was submitted for review on 3 December 1985, approved for publication on 16 Jan 1985, and designated as NSMRL Report No. 1070.

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ABSTRACT

A matching task was used to measure the effects of ambient illumination, raster luminance, and target size on color discriminability in a CRT display. A set of ten easily distinguishable colors was presented under two conditions of ambient illumination (dark and bright) and two conditions of raster luminance (low and intermediate). Below this set, a target color was presented as either a circle of 1.4 degrees diameter or a line 1.4 degrees high and 7 minutes wide. Observers were required to match this target with the appropriate color presented in the display above.

Under the dark ambient illumination, the intermediate raster yielded faster response times and lower error rates than the low raster. Under the bright ambient, significantly more errors were made with the intermediate than low raster luminance. The target circle yielded faster response times and lower error rates than the target line under all conditions.

Color discriminability appears best under conditions where the background luminance is intermediate. Consequently, under dark ambient conditions, raster luminance should be set at an intermediate level but decreased as the ambient illumination increases.

The ability to discriminate among colors presented on self-luminous displays, such as CRT monitors, continues to be an important area of research. It is widely agreed that when color is used for coding purposes in visual displays, the largest increase in performance will result when the colors used are easily discriminable from one another (Carter & Carter, 1981; Neri & Zannelli, 1984; Silverstein & Merrifield, 1985). Past research has shown that many factors can affect the perception of colors and hence their discriminability. For example, as background luminance is increased, perceived saturation increases (Hunt, 1950; Burnham, Evans, & Newhall, 1952; Pitt & Winter, 1974) and hence color discrimination also increases. This effect has an upper limit, however, since increases in the background luminance beyond intermediate levels will result in colors actually appearing more similar and hence less discriminable from one another (Heinemann, 1972; Jacobsen, 1984).

A clear distinction must be made between background luminance and raster luminance. The latter refers to the amount of light emitted from the CRT screen, independent of any ambient illumination. However, in addition to emitting light, almost all CRT screens reflect light incident on the screen. The background luminance is the sum of of these two factors, light emitted and light reflected from the CRT screen. Although an increase in raster luminance will cause an increase in background luminance, the two terms are <u>not</u> synonymous. In the present study it was decided to separately manipulate the ambient illumination and raster luminance to determine any interaction effects between the two on a color matching task that yields a good measure of color discrimination (Luria, Neri, & Jacobsen, in press).

The level of ambient illumination incident upon the CRT screen is known to affect color discrimination substantially. As it increases, both luminance and chromatic contrast are reduced and hence color discrimination is decreased. This is due to a physical color shift in the direction of the ambient illumination. The amount of the shift is dependent on the relative intensities of the ambient illumination and the colors generated on the CRT. The greater the ambient to CRT color ratio, the greater the color shift.

Target size has also been shown to have an effect on color appearance. As target size decreases, colors appear more and more similar and hence more difficult to discriminate (Judd & Wyszecki, 1963; Silverstein & Merrifield, 1985). The distinction between blue and yellow is especially difficult with targets having visual angles of

less than 15 minutes of arc. This phenomenon is referred to as small field tritanopia.

These factors are important to consider when one uses colors in CRT displays. If the colors are not sufficiently discriminable, their application to visual displays may actually be detrimental to performance. Consequently, it is necessary to investigate the interaction between these three factors, raster luminance, ambient illumination and target size.

METHOD

Subjects

Eight laboratory personnel, all having normal color vision, as determined by the AO Hardy-Rand-Rittler Psuedoisochromatic Plates, served as voluntary observers. Those who normally wore corrective lenses did so during the study.

Apparatus

All stimuli were viewed on an Advanced Electronics Design, Inc. Color Graphics Terminal, Model 512, that was driven by a Digital PDP 11/04 laboratory computer. The display stimuli consisted of ten circles presented on the CRT screen in the shape of a push-button telephone keypad: a 3 X 3 matrix with a tenth circle centered below. The dimensions of this stimulus display are given in Figure 1. Each of the ten circles could either contain letters or be completely filled with white or one of the ten colors used in this study and described in Table 1. Target stimuli consisted of either a single letter, a circle with a diameter of 1.4 degrees of visual angle or a line 7 minutes of arc wide and 1.4 degrees high. All target stimuli were presented 8 degrees of visual angle below the ten display circles.

Observers were seated approximately 50 cm in front of the terminal screen presented at eye level. Four lights (two 300 W incandescent bulbs and two 40 W cool white flourescent bulbs) situated about one meter above and behind the observer could be used to cast approximately 620 lx of illumination on the CRT screen under a bright ambient illumination condition. Under a dark ambient condition, all lights in the light-tight room were extinguished. Two levels of raster luminance were employed: low (0.144 cd/m^2) and intermediate (32.273 cd/m^2), measured when all room lights were extinguished. These values represent the two

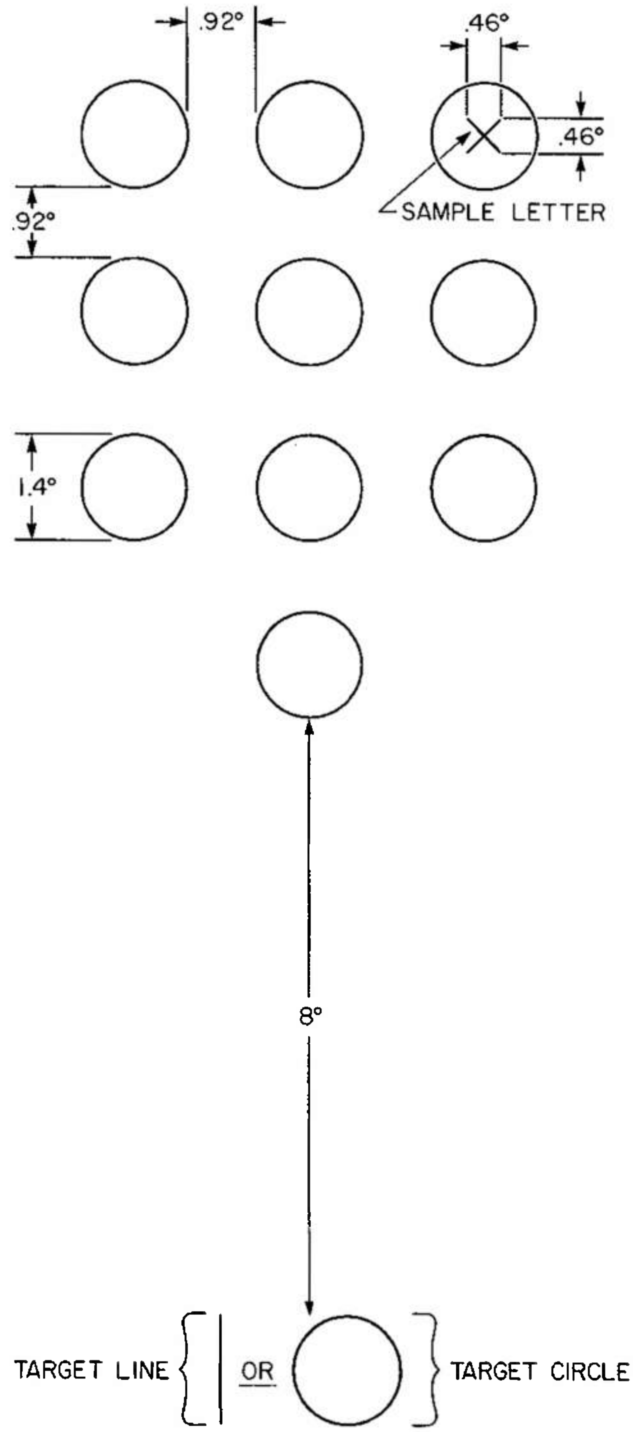

Figure 1. The stimulus arrangement used in this study. Measurements are in degrees of visual angle viewed at a distance of 50 cm.

background luminances under the dark ambient condition. The background luminances for the low and intermediate raster levels under the bright ambient condition were 27.85 and 60.13 cd/m^2, respectively.

Responses were recorded by means of a push-button type telephone keypad that was situated by the observer's preferred hand.

Table 1. Descriptions of the ten colors used in this study under the two ambient illuminations. Relative luminance (Y) is given in cd/m^2. The ΔE^* values represent the estimated minimum perceived color difference (difference between that color and the color most similar to it) based on the CIELUV color system.

	DARK AMBIENT				BRIGHT AMBIENT			
Color	Y	x	y	ΔE*	Y	x	y	ΔE*
Violet	6.71	.277	.145	31.4	34.57	.337	.273	25.3
Blue	9.25	.168	.116	31.4	37.10	.270	.232	28.1
Aqua	101.27	.238	.335	44.6	129.13	.266	.338	37.3
Green	7.37	.312	.572	26.0	35.22	.363	.378	10.5
Yellow	190.45	.423	.466	84.8	218.30	.414	.447	71.0
Orange	81.85	.543	.392	47.1	109.70	.495	.380	44.0
Red	16.68	.607	.322	47.1	44.54	.464	.337	40.0
Pink	135.12	.362	.307	63.6	162.97	.363	.313	40.0
White	307.04	.288	.317	44.6	334.89	.294	.319	37.3
Brown	6.71	.379	.360	26.0	34.57	.372	.350	10.5

Procedure

Observers began with the following practice exercise under the dark ambient illumination and low raster luminance conditions in order to familiarize themselves with the task. The set of ten circles was presented on the screen and each contained a different letter. The observer was allowed to study this arrangement as long as desired. One of the letters was then presented randomly below the set of ten circles and 1 s after a warning tone. The observer's task was to press the button on the keypad corresponding to the location of the target letter in the stimulus display set as quickly as possible without sacrificing accuracy. The response caused the target letter to disappear. After 2 s another warning tone sounded and subsequently another target letter appeared. This procedure continued, using randomization without replacement, until all ten letters were responded to correctly once. The average response time

for the ten correct responses was then displayed to the experimenter and the observer. This procedure was repeated until the average response time became fairly stable, usually about six to seven repetitions. With each repetition, the letters in the stimulus display remained in the same locations but the order of target letter presentation was re-randomized.

Subsequent to this practice session the main experimental session was begun. The procedure was the same as the practice session with the following exceptions. Each of the ten display circles was filled with a different color. The positions of the colors were randomized across blocks of trials and observers. For a given block of trials the ambient illumination, raster luminance and target size were held constant. Each block required the observer to respond correctly to ten target presentations of each color whose order was also randomized.

Half of the observers were presented with the bright ambient illumination first, which was held constant for the first four blocks of trials. The dark ambient was presented on the last four blocks of trials. This order was reversed for the other half of the observers. Under each ambient condition, the raster luminance (low or intermediate) and target size (circle or line) were completely randomized among blocks of trials. Between the two ambient conditions, the observer was given a rest period of approximately ten minutes. Following this rest, a control procedure was initiated. This consisted of displaying ten unfilled circles on the screen. One of the ten was then filled with white 1 s after the warning tone. The observer again responded via the keypad by pressing the button corresponding to the location of the filled circle. Again, ten correct responses were required for each possible position. This control set thus provided reponse times to the same visual display using the same response panel as in the experimental sessions, but without including the time to compare colors and decide on a match (Neri, Jacobsen, & Luria, in press).

Subsequent to the control set, which was run under the dark ambient and low raster conditions, the next set of four experimental blocks was run under the appropriate ambient illumination. During all of the sessions, the computer recorded the response time for all correct responses as well as information concerning incorrect responses such as response time and the incorrect button pressed. The entire procedure lasted approximately 1 1/2 to 2 hours.

RESULTS

Response Times

The average response times obtained with the white circles in the control session were subtracted from the response times obtained in the experimental session for each observer. This ensured that the resulting times (RTs) reflected only the observer's time to compare the colors and decide on a match. These RTs are presented graphically in Figures 2A and 2B. As can be seen from Figure 2A, there was a significant interaction effect between raster luminance and ambient illumination as well as a main effect of target size as verified by a three-way (Ambient X Raster X Target) ANOVA ($F(1,7)=16.70$; $p<.01$ and $F(1,7)=16.54$; $p<.01$, respectively). Under all conditions, the target circle yielded significantly faster RTs than the target line.

The target size factor was, therefore, collapsed in Figure 2B to more clearly depict the interaction between ambient illumination and raster luminance. As can be seen from this figure, the intermediate raster yielded significantly faster RTs than the low raster under the dark ambient ($p<.01$). Raster luminance had no significant effect on RT under the bright ambient. In addition, the RT under the dark ambient was significantly faster than under the bright ambient when the intermediate raster was present ($p<.01$). There were no significant differences between the RTs obtained under the two ambients when the low raster luminance was present.

Response Times for Individual Colors

Figure 3 shows the average RT for each of the colors under the two ambient and two raster conditions. There was a significant effect of color ($F(9,63)=3.70$; $p<.01$) under the combined ambient and raster conditions. Yellow was responded to significantly faster than red, brown, pink, green and violet. In addition green and violet were responded to significantly slower than blue and white, while violet was also responded to significantly slower than aqua and orange according to Newman-Keuls means tests ($p<.05$).

It is also interesting to note that under the dark ambient illumination, response times for all of the colors were faster with the intermediate than with the low raster luminance. Under the bright ambient illumination, this was not true. In addition, it also appears that response times were especially slow for colors having minimum ΔE^* values of 25 or less.

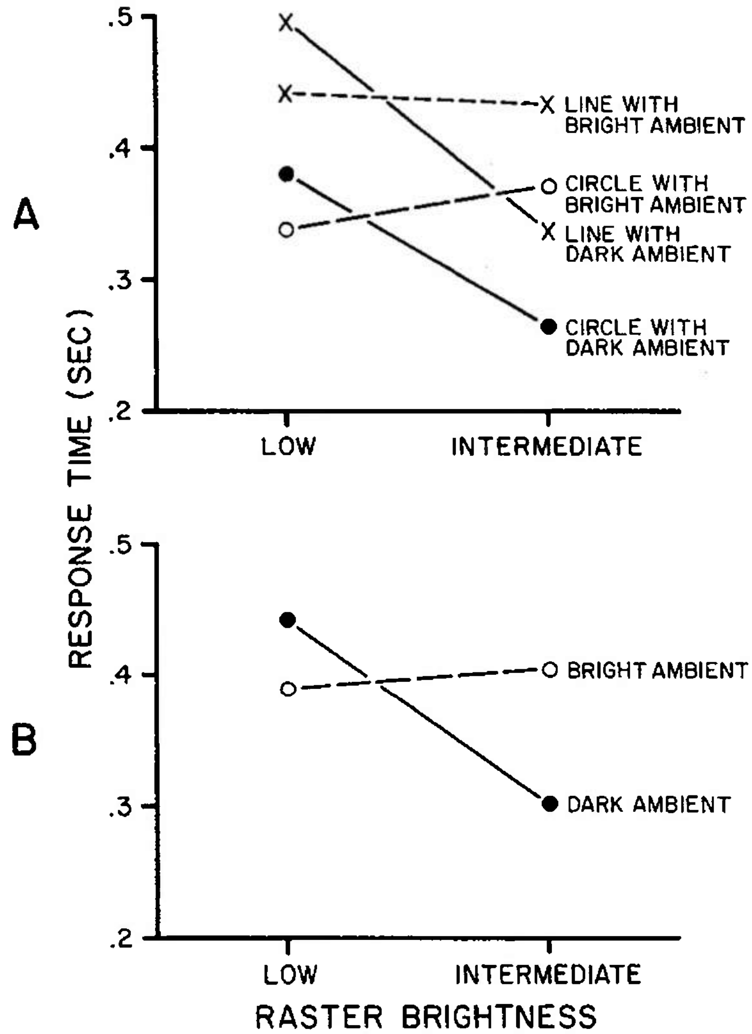

Figure 2. A. RT as a function of target size, ambient illumination, and raster luminance (brightness). B. RT as a function of ambient illumination and raster luminance (brightness). Target size has been collapsed in this graph.

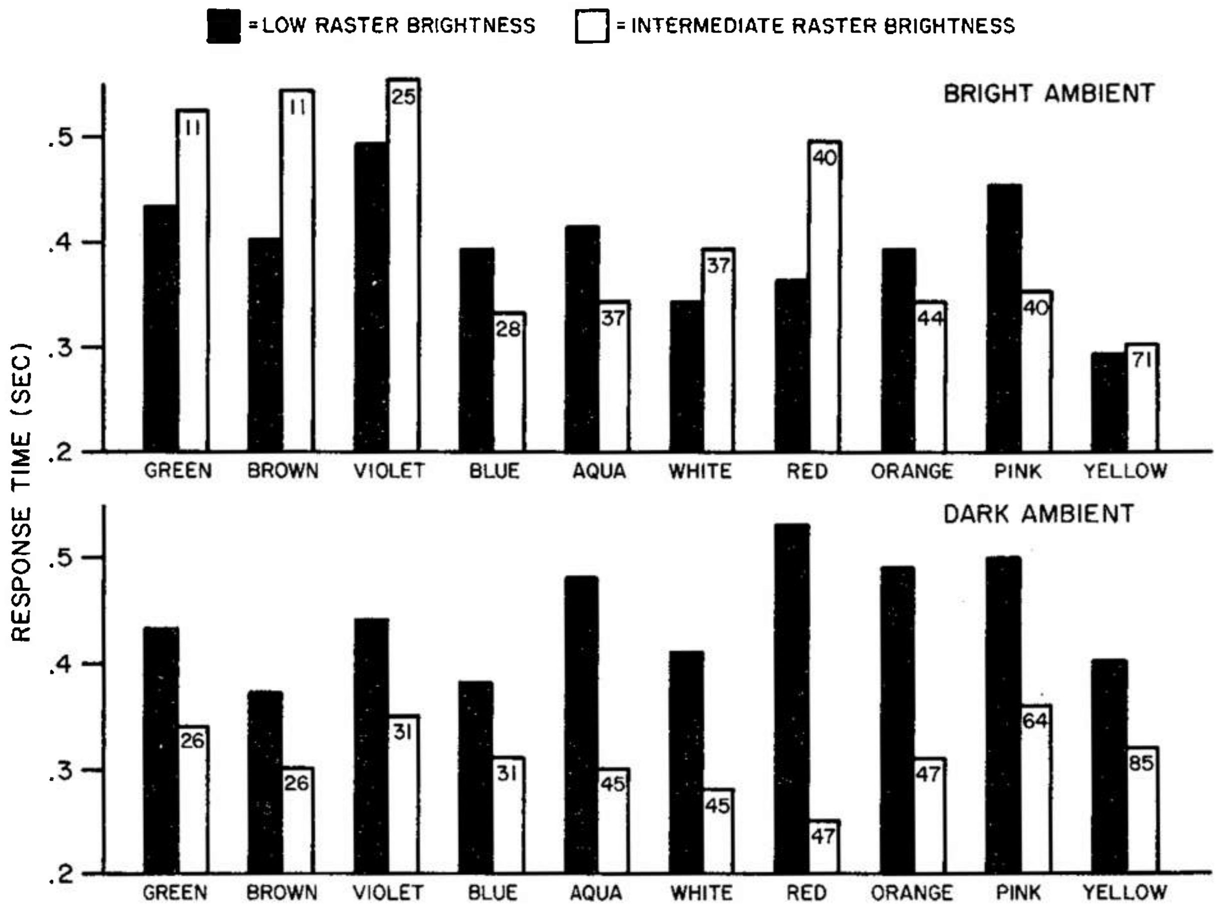

Figure 3. RT as a function of color, ambient illumination, and raster luminance (brightness). The bright ambient illumination data are presented in the top graph while the dark ambient illumination are presented in the bottom graph. The numbers in the bars represent the minimum ΔE^* values for each particular color.

Error Rates

An analysis of the error rates revealed trends similar to those found with RT. Figure 4A depicts the mean error rate for each of the eight experimental conditions. As can be seen from this graph, the target circle always yielded significantly fewer errors than the target line as verified by the three-way (Ambient X Raster X Target) ANOVA ($F(1,7)=6.39$; $p<.05$). In addition, this figure also depicts a significant interaction between ambient illumination and raster luminance ($F(1,7)=20.44$; $p<.01$).

In order to more clearly see this interaction, the target size factor was collapsed in Figure 4B. As can easily be seen from this graph, the effect of raster luminance was strongly influenced by the ambient illumination. Under dark ambient illumination, the intermediate raster yielded significantly fewer errors than the low raster ($p<.01$), while under the bright ambient the opposite effect was found: the intermediate raster yielded significantly more errors than the low raster ($p<.05$).

From this graph, it is also apparent that when the low raster luminance was presented, significantly fewer errors were made under the bright ambient than under the dark ambient ($p<.05$). However, when the intermediate raster luminance was present, significantly fewer errors were made under the dark ambient than under the bright ambient ($p<.01$).

Color Confusions

Not all of the errors committed by observers were color confusions, as they sometimes reported hitting the wrong button on the response keypad. This was also apparent in looking at a confusion matrix where many isolated errors were made between colors that should be easily discriminable for color normals. Hence, in looking at color confusions, it was decided to include only those confusions where more than a total of five errors were made. A list of these is presented in Table 2. As can be seen from this table the two worst color pairs in terms of being easily confused were violet/blue and green/brown. The ΔE^* values (an estimate of perceived color difference based on the CIELUV color system) were lowest for these two color pairs. Under the dark ambient, the ΔE^* value for the green/brown pair was 26.0 while it was 31.4 for the violet/blue pair. Under the bright ambient the values were 10.5 and 28.1, respectively.

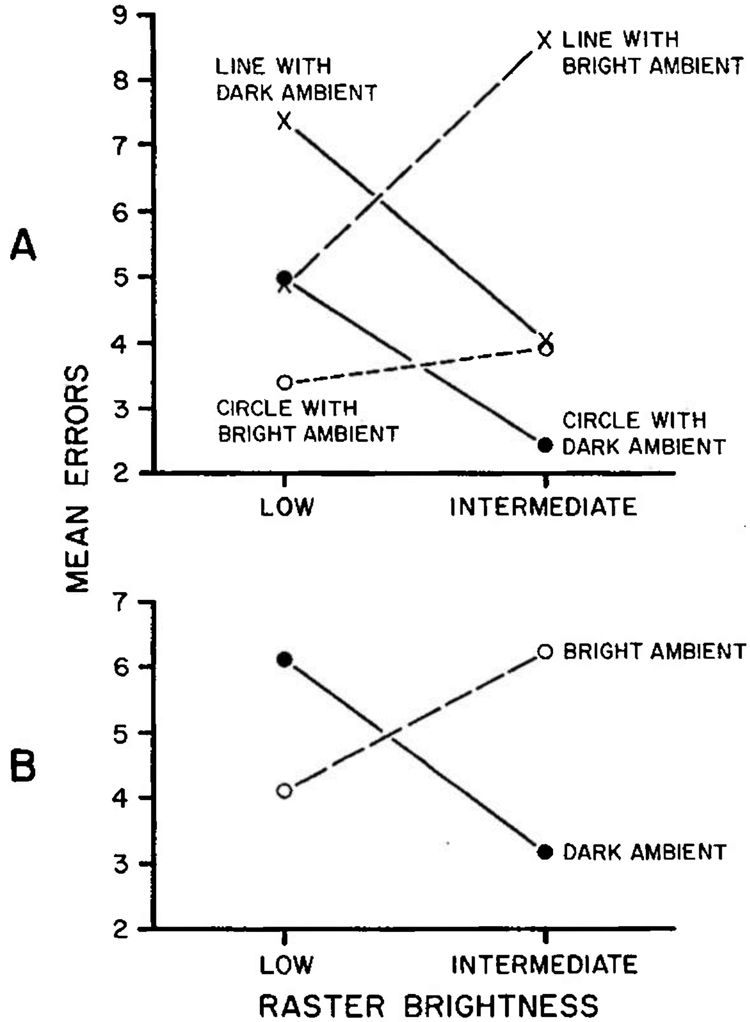

Figure 4. A. Mean errors as a function of target size, ambient illumination, and raster luminance (brightness). B. Mean errors as a function of ambient illumination and raster luminance (brightness). Target size has been collapsed in this graph.

Table 2. Number of color confusions summed across all observers.

Dark Ambient		Bright Ambient	
Low Raster	Intermed. Raster	Low Raster	Intermed. Raster
Vio/Blu 6	Grn/Brw 14	Vio/Blu 8	Vio/Blu 25
Grn/Brw 7		Grn/Brw 13	Grn/Brw 34
Red/Ora 20		Red/Ora 6	Red/Ora 9
Wht/Pnk 6			

DISCUSSION

The most important finding of this study was the interaction between raster luminance and ambient illumination on performance. It is clear from these data that there is not one raster luminance that is best for all levels of ambient illumination. Under dark ambient levels, an intermediate raster luminance yielded significantly better performance than a low raster. This was true for both target sizes. However, under the bright ambient illumination, the intermediate raster yielded poorer performance than the low raster. Although there were no significant differences in response times between the two raster conditions under the bright ambient, there was a highly significant increase in errors when the intermediate raster was present. This finding is worthy of further discussion.

As previously stated, it is well established that increasing background luminance serves to increase the perceived saturation of colors. However, in the present study a distinction had to be made between raster luminance (light emitted from the CRT screen) and background luminance. The latter is the sum of the former and the amount of ambient light reflected off the CRT screen. Consequently, under the dark ambient/low raster condition, the background luminance was lowest and performance, both in terms of errors and RT was poor. Under both the dark ambient/intermediate raster and bright ambient/low raster conditions, the background luminance was at an intermediate level and performance was good. Finally, under the bright ambient/intermediate raster condition the background luminance was at its highest and performance began to deteriorate, especially as measured by error rate. This finding is in accordance with results obtained by Heinemann (1972) and Jacobsen (1984) where surround to target luminance ratios greater than about 100:1 resulted in all

colors appearing about the same shade of gray, i.e., black. The effect on color discrimination of increasing background luminance from 0 to infinity can be described as an inverted-U-shaped function. Hence, the best performance measures can be expected with intermediate background luminances. This is also supported by previous studies by Williams (1967) and Jacobsen (in press).

An intermediate background luminance can result from two situations. One is through the increase of raster luminance under dark ambient illumination. The second is through an increase in reflected light resulting from bright ambient illumination incident upon the CRT screen. The latter method, however, has the disadvantage of also reducing all of the luminance and chromatic contrast ratios among targets presented on the screen. This, of course, has a detrimental effect on color discriminability.

As the best color discrimination occurs with an intermediate background luminance, raster luminance should be allowed to vary as a function of ambient illumination incident on a CRT screen. The raster luminance should be set at intermediate levels under low ambient conditions but decreased as the ambient illumination increases. This will result in the greatest amount of discrimination among colors presented on the screen.

Performance, as measured by both error rate and response time, was also affected by target size. Clearly, better performance was obtained with the target circle than the line. This finding was not at all surprising and has been previously reported many times in the literature (Judd & Wyszecki, 1963). This result is significant for incorporating color into displays where color is used to encode information in items with small visual angles such as alphanumeric characters. As the visual angle decreases, the physical difference between the colors must be increased in order to maintain a constant perceived difference between colors. This effect of target size only begins to become noticeable for target sizes of less than about 1 degree of visual angle, however (Cowan, 1982).

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

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appropriate color presented in the display above.

Under the dark ambient illumination, the intermediate raster yielded faster response times and lower error rates than the low raster. Under the bright ambient, significantly more errors were made with the intermediate than low raster luminance. The target circle yielded faster response times and lower error rates than the target line under all conditions.

Color discriminability appears best under conditions where the background luminance is intermediate. Consequently, under dark ambient conditions, raster luminance should be set at an intermediate level but decreased as the ambient illumination increases.